Zero Emission Commercial Air Transport

Let's get started.

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1 Executive summary

Reduction of carbon emissions is one of the largest challenges of society today and extremely challenging for the aviation industry. While the world transitions to sustainable energy use, aviation will become a lagging sector due to its inherent technological challenges to reducing emissions.

The industry currently focuses on radical new aeroplane designs and Sustainable Aviation Fuels (SAF) to enable emission reduction on long-distance flights. Capacity and efficiency limitations push the earliest operational occurrence of zero emission flight by SAF at a significant scale to 2040. The reputation of aviation can be served by any form of zero emission flight before this time.

By theoretical analysis of the state of technology this article induces that there is a niche in short distance aviation comprising up to 20% of the total aviation market where flight by Electric Propulsion (EP) can readily be viable, and where it will remain a preferred method of flight for the long term.

To maximise environmental and commercial benefits in the EP niche, and to demonstrate the commercial applicability of zero emission aviation, the time to build towards a first mover electric aviation operation is now.

Finally, this article proposes a plan and time schedule to realise an electric aviation operation.

2 Research and key takeaways

2.1 Urgency

The aviation industry is under immense pressure to reduce carbon emissions. The inherent dependency on large thrust to weight ratio for energy storage and propulsion systems makes aviation one of the most challenging sectors to transition. It will therefore need to wait for significant advancement of energy technologies and will be preceded by many industries in transportation and manufacturing. It can therefore be considered as one of the final frontiers of sustainability (more info).

Transport is one of the largest contributors of emissions in the EU (more info) and rapid progress is made through reduction policies. Aviation represents some 13% of transport emissions. As emission reduction in other modes of transport is driven by more ready technological viability, aviation will lag due to its inherent challenges. Aviation will therefore become a more significant source of emissions, the effect of which is already impacting operators in many European countries as they are subjected to straining carbon reduction policies, while confronted with limited options. This challenging situation led to initial policy relief. (more info)

Aside from this, large parts of aviation are by many considered a replaceable mode of transportation (more info). This will become a more popular school of thought as emission reductions will advance faster in ground transport compared to air transport.

In addition, new generations are becoming increasingly influential in the business environment. These generations are more wary of the environmental situation and will more actively seek solutions by changing services, modes, and adapting their lifestyle faster than previous generations (more info). This will deteriorate the reputation of aviation if no steps towards improvement are made. The effect of this influence will become apparent well before 2030.

2.2 State of technology

2.2.1 Efficiency of the power delivery chain

The state of the art for low-emission aviation is based on two main tiers of development: Electric propulsion (EP), and Sustainable Aviation Fuels (SAF) (more info). The latter may form a near drop-in replacement for high energy density and low weight jet fuel (Jet A-1) in [relatively] conventional aeroplanes, and will enjoy the benefits of the gas turbine engine, which has proven to provide a suitable high thrust to weight ratio.

EP is limited by the state of the mass density of the energy storage, which can be in the form of batteries or (hydrogen) fuel cell technology. At the moment the largest challenge is the relatively low energy mass density of batteries (a factor 40 less than Jet A-1), the high weight of high-power fuel cell technologies, and the high volume required for hydrogen storage.

To understand the total efficiency (η_p) of the energy delivery and propulsion system, the efficiencies of the subsystems should be considered. In the compared cases we can assume; an equal zero emission energy source (wind, solar) as starting point, and an equal shaft-power to thrust power conversion (propeller) at the end and therefore we can reduce our equation to the product of the efficiencies of the enclosed processes in the chain:

$$\eta_t = \eta_p * \eta_e * \eta_c$$

Where η_p represents the efficiency of the process to store electrical energy into the storage medium (i.e. batteries, synthetic fuels, hydrogen), η_e represents the efficiency of the extraction of the energy from the medium, and η_c represents the efficiency of the conversion of energy to shaft power.

Currently the efficiency of the usage of SAF is limited by the efficiency of the fuel production and the fuel to work conversion processes.

The manufacturing of SAF is zero emission by using a process to electrically produce liquid fuels from carbon that is extracted from the air so as to compensate the carbon released during combustion. Using a carbon-neutral electricity source it is possible to produce a carbon-neutral drop-in replacement for Jet A-1. The highest realistically achievable efficiency of fuel production is about 70% (more info).

The most significant loss in the energy chain lies in the gas turbine combustion engine with practical mechanical conversion efficiencies well below 25%. Secondly, although SAF can be produced strictly carbon-neutral, it will not prevent Contrail Cirrus and Soot emission when burned (more info).

In contrast, electric drivetrains allow efficiencies of over 98% for charging, 98% for discharging (more info), 95% for electric power conversion and regulation, and 95% for electromechanical power conversion. As can be seen in figure 1, the total chain efficiency of the system energy delivery and conversion in a battery-electric airplane therefore can be over 85% at the current state of technology, compared to significantly lower efficiencies of hydrogen fuel cell technology (more info) and only 15% total chain efficiency with SAF. Battery electric supply and drive trains can therefore be nearly five times more efficient than SAF, requiring less energy required to be stored in the aeroplane. This reduces the problem of energy mass density in the weight of the required energy storage installation in the airframe from a factor 40 to 8.

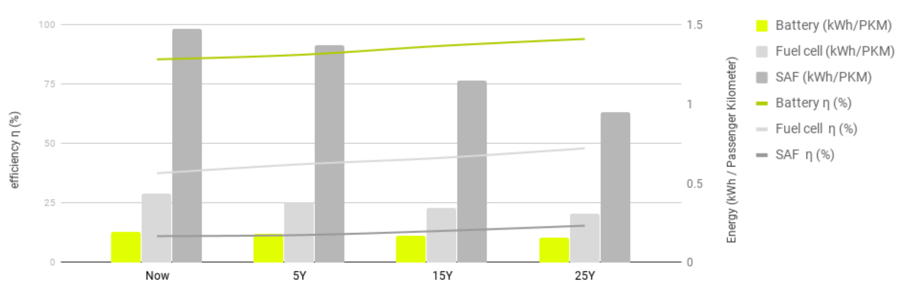

Figure 1: Efficiencies and energy use per Passenger-Kilometer (PKM) for the discussed power chains and their expected progression by techonology maturation. The compared chains comprise of power conversions after electricity production and up to shaft power generation for a 4500Kg (turbo)prop aeroplane. The effects of mass reduction due to the en-route burning of fuel and the jet-thrust contribution of exhaust gasses have been accounted for in determining comparable power requirements.

Put simply: aviation fuels have a 40 times higher mass density than current batteries. But considering the on-board conversion of energy to thrust, an electric airplane will need to bring only 8 times, not 40 times more energy storage mass in batteries to achieve the same range. This is an often overlooked factor.

Using today's state of technology, making no other alterations than switching out the gas turbine and fuel tanks of a turboprop aeroplane with [hypothetical drop-in replacement] e-motor and batteries, any current aeroplane will have at least $\frac{1}{8}$ of its current endurance at equal useful load. If useful load is reduced, even longer missions become available. This makes short-distance (up to 400 Km) missions readily viable in the short term.

2.2.2 Efficient allocation of scarce resources

In the long term, the efficient allocation of zero emission energy should be considered. While the world transitions to zero emission energy production from 25% of total now to 85% in 2050, total supply and conversion efficiency will remain a highly important driver in the use and allocation of energy. I therefore expect that SAF will be regarded as an inefficient use of scarce renewable energy, and should where practicably replaceable with a better alternative, be avoided.

As can be derived from figure 2, the share of <500km flights is significant when compared to the distance distribution of European flights.

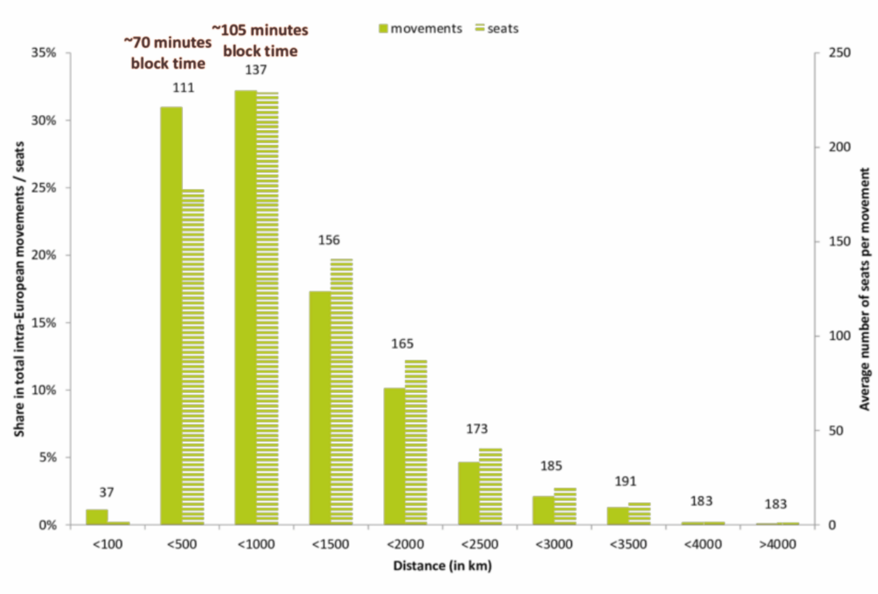

Figure 2: European flight movements and seats at discrete distance ranges. (Source: DATASET2050 "Data driven approach for a Seamless Efficient Travelling in 2050", DATASET2050 consortium, 2016)

When regarding <500km flights, which is in the EP feasible range, EP is well positioned to be a long term alternative to SAF and High Speed Rail (HSR). EP will in addition rule out any secondary negative effects of combustion engines such as Contrail Cirrus and Soot emissions with SAF (more info), and significant infrastructure construction and lifetime emissions with HSR. (more info). This is independent of the fact that the currently viable small scale EP airplane can not profit from the advantages of the scale of the large scale SAF airlines and HSR examples used.

Type/mode	energy (kWh/PKM)	remarks
SAF <500km	0.91	(click for source)
SAF >500km	0.62	A321 NEO
EP	0.18	EP converted PC-12, 5 pax
HSR	0.06	(click for source)

Table 1: Comparison of efficiencies of zero emission energy allocation

2.2.3 Technology development considerations

Battery energy mass density development can profit from orders of magnitude higher worldwide investment and experience gained through other industries (for example automotive) compared to SAF technology development. (more info)

At the moment of writing, the highest achievable battery densities exceed 300Wh/kg. It is expected, with a conservative increase in energy density of 6% per year, a threshold of 400Wh/kg will be passed before 2025, enabling viability of 500km flights, opening up profitable operational opportunities. The last decade has seen battery density increases of over 12% per year. (more info)

2.2.4 Technology time to market

Aviation is bound by strict safety regulations. One of the main premises of safety is to provide a reliability that allows below 10^{-9} failure rate. New aircraft and aircraft components will therefore require stringent testing and certification tracks before EASA type certification will allow commercial operations. Next to the battery energy density developments, this is the most important factor to influence time to market. Certification of components that do not strictly depend on the battery chemistry can, however, already be started while waiting for battery chemistries to further mature and increase mass energy density.

2.2.5 Incremental innovation

To prevent unexpected technical challenges and a large amount of certification processes, it is necessary to use as many proven components as possible. It is therefore important to not design a completely new aeroplane from scratch. It may very well be possible to apply for supplemental type certificates on existing certified aeroplanes and that swapping out engines and fuel systems with newly certified motors and batteries, along with the addition of a limited number of auxiliary systems (i.e. non-turbine dependent cabin pressurisation and de-icing) may be the minimal required steps. This contrasts the approach of most electric aviation initiatives, which choose to certify newly designed aeroplanes, and will therefore have significantly increased risk of delays and certification problems in the testing and certification phases. (more info) (more info)

2.2.6 Battery usage

Lithium batteries have a limited cycle of approximately 80% performance after 1500-2000 full charge-discharge cycles, which when considering endurance reserve for diversions, results in about 2500-3000 flight cycle-life, requiring them to be replaced every 2-3 years in commercial operational conditions. The cost of replacement is competitive compared to combustion engine inspection and maintenance costs and the environmental impact of this replacement is low due to the recyclability of Lithium batteries. (more info)

This biennial replacement cycle offers two opportunities in the startup years of an electric aviation operation:

Firstly, it allows for the continuous certification and replacement of state of the art battery systems. This allows aeroplanes to be continuously updated with better mass-density batteries, increasing their endurance and useful load over the airframe lifetime.

Secondly, batteries will be replaced when they can not meet airborne certification criteria anymore. However, they still have significant capacity and residual value, which allows them to be used in a second life to buffer power grid demand on the ground when fast-charging aeroplanes before entering recycling.

2.2.7 Operational cost

Although it will take years before electric aeroplane maintenance can compete with the gained experience from a long history of usage of turbine engines, electric drivetrains profit significantly from lower operation temperatures, less moving parts and solid state components when compared to combustion engine drivetrains. The overall complexity of the aeroplanes will be reduced. This impacts operational costs significantly. The lower power consumption of the full energy chain will further reduce operational costs.

2.3 Market

2.3.1 Niche size

As established before, EP will be the most desirable short range solution where technically feasible. Initially this may represent a share of up to 25% of European Pax seats.

For the next 25 years, EP may be the only [efficient] form of fully zero emission aviation due to the limited availability of zero emission energy to fully service SAF.

2.3.2 Reputation

As mentioned, zero emission aviation can be considered the final frontier of sustainability, and achieving significant progress in it has high the potential to significantly raise the reputation of the industry. Initial operations will be able to profit from early adopters that are willing to pay a premium.

Considering an increasingly aware business and consumer population, there will be a high demand for sustainable transport and the most important competitor for aviation will be HSR (more info).

While aviation in the short term will be unable to regain a sufficient sustainable reputation compared to HST, it will retain its appeal and allure to many. There is a higher value perception in flight, when efficiently handled, compared to HST.

2.3.3 On demand Business Aviation

Initially, electric flight operations will be limited to up to 9pax size aeroplanes. This opens additional opportunities for operations. The small size and takeoff weight allows the use of General Aviation (GA) services at large hubs, and can make operations available at smaller aerodromes. GA-services allow the avoidance of commercial air transport terminals, which opens the opportunity to speed up the boarding and off-boarding process, an often perceived cumbersome disadvantage of aviation. These time gains may lead to shorter travel times and higher value perception. Sustainable regional flight with small aeroplanes has also been recognised as an opportunity to build a fine-grained network as opposed to the current hub-and-spoke model of aviation networks (more info)

Business Aviation and air taxi operations remain a significant niche in the short hop business travel market. In fact COVID-19 has seen increased growth in this niche due to the desire of business travelers to travel in smaller groups, limiting their exposure. (more info)

Additionally, the significantly reduced noise production of electric motors compared to turboprop engines will allow increased operations of aerodromes in densely populated areas, opening opportunities for travel time reduction.

3 Conclusion and solutions

In 2020, the potential for battery electric flight is significantly underestimated.

Firstly, because it is readily achievable. Electric motors and lithium batteries allow for 750Kw thrust levels (currently in use by up to 9pax transport category aeroplanes) at acceptable and rapidly improving mass energy density, which are suitable for profitable operations. EASA has certified its first 2-seater electric aeroplane within the EASA CS-23 certification specification that will also be applicable to the proposed EP converted <9pax aeroplane.(more info).

Secondly, we established its short term and mid term realistic ranges of 250-500km that can compete in a market of up to 25% of flight movements. It has therefore also a significant place for the long term. This is an important factor for the legitimation of investment in early stage technology.

There is uncertainty in predicting the outcome of preferred modes of transportation and energy delivery, which delays investment in zero emission aviation technology. However, due to the strict safety regulations that apply to the aviation industry, any investment made at the moment when certainty of technology choice will be better, will still leave years of certification and testing to be done, even on technologies that are readily available.

Therefore it is of strategic importance to start testing and certification of components of EP technology as soon as possible. By starting certification of electric motors, power converters and newly required auxiliary technology, costly time can be saved until batteries (or perhaps even new alternatives) reach the required energy density level.

Additionally it is very important to consider that once electric flight becomes broadly viable and gains public interest, a shortage of production capacity on components and airframes will soon occur due to the small scale nature of achievable electric flight and the low production numbers of small scale aircraft. An early mover will be able to secure a position in scarcity until production picks up.

The scarcity in the early stage is in fact an additional value creation tool. Once electric flight becomes available, there will be limited seat availability in a business environment that has a high demand. This can be used to leverage luxury market business models that increase the profitability of the future operation.

Testing and certification is an investment-intensive process, so before anything, it is important to build and execute a financial plan. The financial risk can be largely limited by pre-selling or pre-reserving seats that become available once the operations start. Pre-selling tickets to early adopters will also provide market insights for the future business model. Therefore an important part of this proposed plan is to start finding committed partners that recognize a demand for zero emission aviation tickets.

4 Action plan

Below I will set out a proposed action plan for the realisation of commercial electric flight operations.

1. Foundation of a basic research and preparation organisation - 2020 Q3
   (a) Publish article
   (b) Select and involve technology partners

(c) Determine realistic viability
(d) Seed investment round

2. Establish market and future customer base - 2020 Q4
    (a) Market research
    (b) Business modeling
    (c) Recruit early adopters preselling flights in the early operational years
    (d) Establish covenant of committed early adopters
3. Preparation of testing and certification - 2021 Q2
    (a) Establish testing and certification plan with technology partners
    (b) Initiate certification process with EASA
    (c) Conclude financial projections
    (d) Series A investment round
4. Establish a testing and certification facility (ex-battery tech) - 2021 Q3
    (a) Hire human resources
    (b) Acquire material resources (airframes)
    (c) Execute testing and certification plan with technology partners and EASA
    (d) Establish fleet acquisition plan
5. Set-up operational prerequisites - 2021 Q3
    (a) Select and involve operational partners
    (b) Execute fleet acquisition
    (c) Finalise operational services and business models
    (d) Monitor battery hydrogen fuel cell energy density
6. Initialise rolling battery (or alternative) technology certification - 2023 Q1
7. First flight of operationally certified aeroplane - 2024 Q3
8. Start of operations of <350km legs - 2025 Q1
9. Start of operations of <500km legs - 2026 Q1

5 About the author

Tom Vroemen (1985) holds an EASA pilot's licence, a bachelor's degree in Mechanical Engineering, a master's degree in Organisation & Strategy and is an Executive MBA candidate at HEC Paris. He worked for TNO and BAM and founded CrowdAboutNow, Ripple and BuzzMaster. He has been recognized with several innovation and sustainability awards (linkedin) (website).